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Triggered Star Formation in the Scorpius-Centaurus OB Association (Sco OB2)

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Abstract.
We explore the star formation history of the Upper Scorpius OB association, the youngest part of Sco OB2. A wide field (160 square-degree) survey for low-mass pre-main sequence (PMS) stars enabled us to increase the number of known low-mass members of Upper Scorpius to nearly 100 stars. In a detailed analysis of the locations of these stars in the HR diagram, taking proper account of the uncertainties and the effects of unresolved binaries, we find a mean stellar age of about 5 Myr and no evidence for a significant age dispersion among these stars. This implies that the star formation history of the Upper Scorpius association was dominated by a short star-burst, which started about 5 Myr ago and ended probably not more than one or two Myr later. Interestingly, the structure and kinematics of the HI shells surrounding the Sco OB2 association show that the shock wave of a supernova explosion in the nearby Upper Centaurus-Lupus association, the oldest part of Sco OB2, crossed Upper Scorpius just about 5 Myr ago. This strongly suggests that this supernova shock wave triggered the star-burst in Upper Scorpius.

1. Introduction

OB associations are thought to be the dominant birthplaces for the low-mass field star population (Miller & Scalo 1978; Zinnecker et al. 1993; Brown et al. 1999). A good knowledge of their formation history, their stellar content, and their evolution is therefore crucial for our understanding of the galactic evolution. Also, OB associations offer a very good opportunity to study the origin of the field star initial mass function: they contain the full range of stellar masses, and since they are very young, their mass function can be inferred with minimal corrections for stellar evolution. Furthermore, the presence of numerous massive stars creates physical conditions that can be very different from those in regions where only low-mass stars form. The massive stars affect their environment mainly by their ionizing radiation, their stellar winds, and finally by supernova explosions. In the immediate neighborhood of the massive

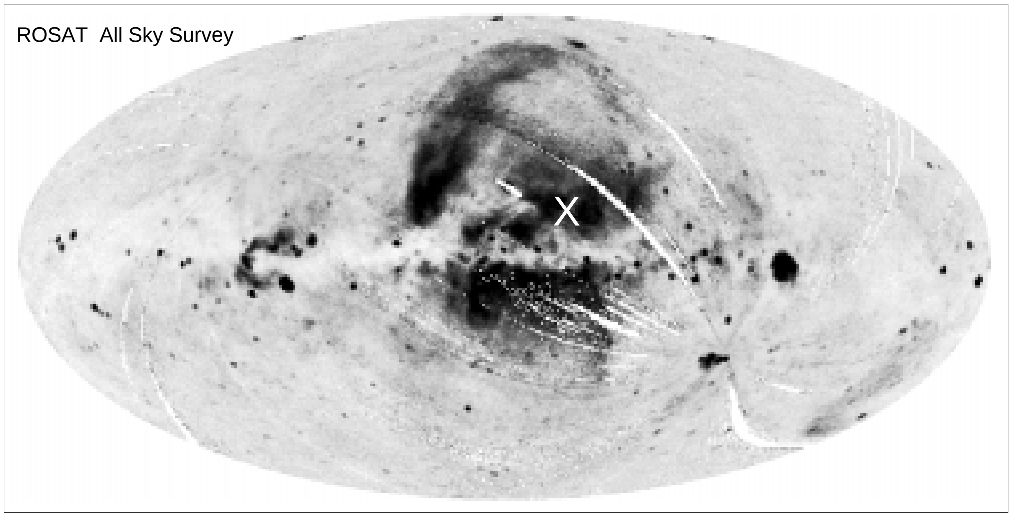

Figure 1. All sky map of the diffuse soft (0.75 keV) X-ray emission, created from the data of the ROSAT All-Sky Survey (Snowden et al. 1995). The large white X symbol slightly above and to the right of the middle marks the center of the Scorpius-Centaurus association. The huge (diameter $\sim 120^\circ$) roughly spherical feature of enhanced X-ray emission around Scorpius-Centaurus is caused by the hot gas in the supernova- and wind-blown bubble that was created by the massive stars in Sco OB2.

stars, these effects are mostly destructive, since they tend to disrupt the parental molecular cloud. At somewhat larger distances, however, the shock waves caused by stellar winds and supernova explosions can induce collapse of molecular cloud cores and thus start star formation, if the right conditions are met (see Section 5). Thus the comparison of the stellar content and the star-formation history of OB associations to those of low-mass star forming regions lacking massive stars, like the Taurus-Auriga T association, can yield important information about the influence of massive stars on the star formation process: it allows a comparison of isolated star formation under rather quiescent conditions in T associations versus clustered star formation in the violent environment of OB associations.

2. The Sco OB2 association

At a distance of only ~ 140 pc, the Scorpius-Centaurus association is the OB association nearest to the Sun. It contains several hundred B stars which concentrate in the three subgroups Upper Scorpius (the youngest subgroup), Upper Centaurus Lupus (the oldest subgroup), and Lower Centaurus Crux (cf. de Zeeuw et al. 1999). The area is essentially free of dense gas and dust clouds, probably the consequence of the massive stellar winds and several supernova explosions, which have cleared the region from diffuse matter and created a huge system of loop-like H I structures around the association (cf. de Geus 1992). The winds and supernova explosions from the massive stars in Scorpius-Centaurus

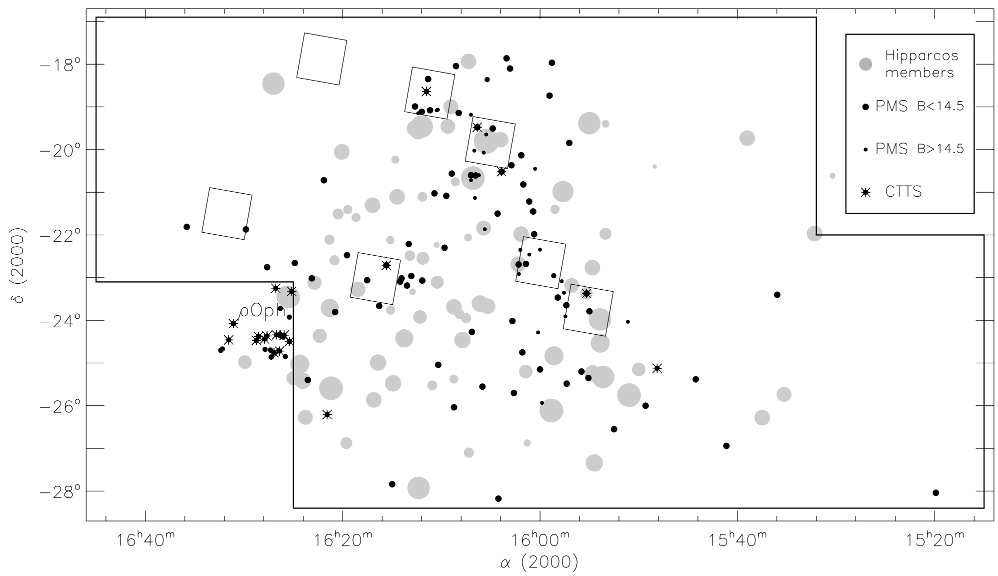

Figure 2. Map of our field in Upper Scorpius region, marked by the thick solid line. The low-mass PMS stars are shown as solid dots, the Hipparcos high-mass members as big grey dots with symbol size proportional to the logarithm of their luminosity. The squares show the fields investigated by Walter et al. (1994).

also created a huge bubble of hot gas, that can nicely be seen in X-ray (see Figure 1) or radio images and constitutes the largest structure visible on the sky at these wavelengths.

The Scorpius-Centaurus association in general, and Upper Scorpius in particular, was very well investigated by the astrometry satellite Hipparcos. De Zeeuw et al. (1999) studied the kinematics of the stars in Scorpius-Centaurus and could identify 120 members to Upper Scorpius by their space motions. From this study, the population of high-mass ($M_* \gtrsim 3\,M_\odot$) members of Upper Scorpius is completely known. Furthermore, the ages of these high-mass members are also well known: De Zeeuw & Brand (1985) and de Geus et al. (1989) independently derived an age of $5-6$ Myr for the B stars in Upper Sco and found no evidence for a significant age spread among these stars.

3. The low-mass stellar population of Upper Scorpius

While the population of high-mass stars in Upper Scorpius is well known and investigated, not much was known about the low-mass members until recently. If the mass function of Upper Scorpius follows the Miller & Scalo (1979) field star IMF, one would expect roughly 1500 low-mass ($M_\star < 2\,M_\odot$) members to be present. In order to identify a statistically unbiased, magnitude limited sample of low-mass members, we have performed a systematic search for PMS stars in Upper Scorpius. Extending previous investigations of small parts of Upper

Scorpius by Walter et al. (1994) and Kunkel (1999), we have surveyed an area of 160 square-degrees, covering the full extent of the association. By follow-up observations of ROSAT All Sky Survey X-ray sources we were able to identify numerous new PMS stars by their strong lithium absorption lines. This allowed us to increase the number of known PMS stars in Upper Scorpius to ~ 100 objects (for all details see Preibisch et al. 1998). In Fig. 2 we compare the spatial distribution of the low-mass members to that of the high-mass members identified by Hipparcos. Both populations show a similar, more or less homogeneous distribution within a roughly circular area with a radius of some 6° near the center of our field.

Following the optical characterization of the ~ 100 low-mass PMS stars, we have placed these stars into the HR diagram (Fig. 3). The usual way to interpret such a HR diagram is to derive the mass and age of each star from its location in the diagram by comparison with PMS models. However, there are several problems associated with such a procedure which make the interpretation of the derived ages and masses difficult. One problem is that any measurement errors, for example uncertainties in the photometric data used to determine stellar luminosities, will cause errors in the derived stellar masses and ages. Also, not all stars in the association will be at exactly the same distance, adding uncertainty to the stellar luminosities that have been determined on the adoption of the mean distance of the association. Another important problem is that the ages derived from the position in the HR diagram will systematically underestimate the true ages because of the presence of unresolved binary systems.

We thus decided to use a different approach for our study of the age structure of the association. As described in detail in Preibisch & Zinnecker (1999), we simulated the location of the members of a model star cluster with a given age distribution in the HR diagram, taking proper account of the sources of errors mentioned above. The resulting region in the HR diagram can then be compared to the observed location of the stars and tell us whether the underlying assumptions are consistent with the observations or not. We find (see Fig. 3) that the location of the PMS stars in the HR diagram is fully consistent with a model assuming that all stars have an age of 5 Myr. The mean age of the low-mass stars thus agrees very well with the $5-6$ Myr previously found for the age of the massive stars and shows that low-mass and high-mass stars are coeval and co-spatial and thus probably have formed together. The absence of a significant age dispersion (our modeling suggests that the spread in stellar ages is smaller than about 2 Myr) implies that all stars in the association have formed more or less simultaneously. This means that the star-formation process must have started rather suddenly and at the same time everywhere in the association, and also must have ended rather suddenly after at most a few Myr. The star formation process in Upper Scorpius thus can be considered as a burst of star formation during which the stars have been forming much faster than typical for the quiescent conditions in T associations, where the stars seem to form more continuously over time. If all stars in Upper Scorpius have formed within a period of $\lesssim 2$ Myr, the star formation rate was $\psi \gtrsim 1 \times 10^{-3}\, M_\odot/\mathrm{yr}$. This is at least one order of magnitude higher than the typical star formation rate in extended T associations (cf. Feigelson 1996), but quite comparable to the star formation rate in the Orion Nebula cluster (cf. Hillenbrand & Hartmann 1998).

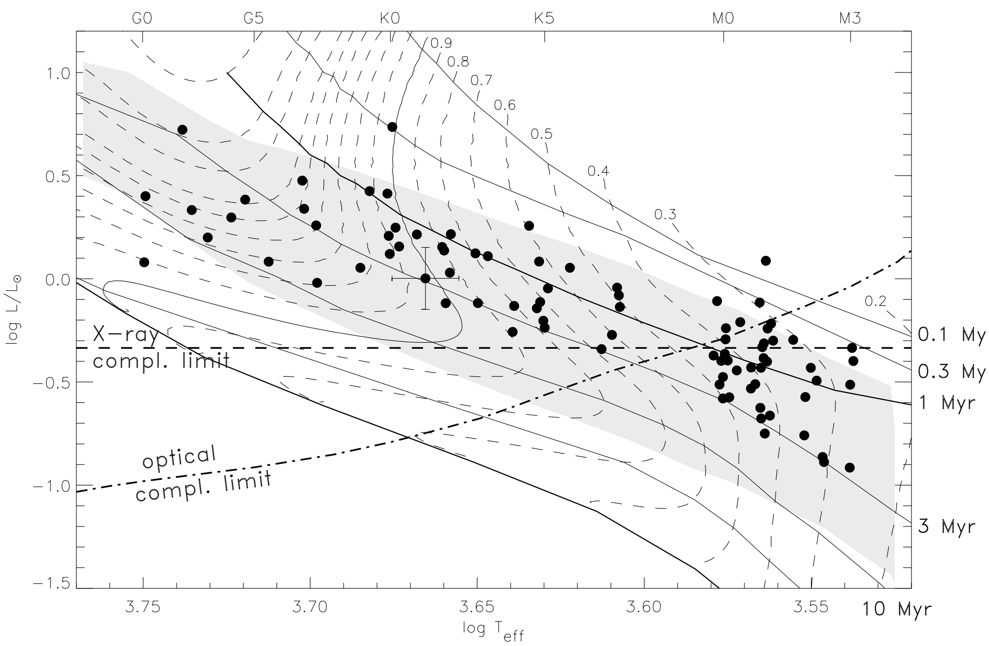

Figure 3. HR diagram for the Upper Scorpius PMS stars compared to the PMS model of D'Antona & Mazzitelli (1994). The grey shaded band shows the region in which we expect 90% of the PMS stars to lie, based on the assumption of a common age of 5 Myr for all stars and taking proper account of the uncertainties and the effects of unresolved binaries (for details see Preibisch & Zinnecker 1999).

To summarize, our results suggest that the star formation history of Upper Scorpius is characterized by

- a nearly simultaneous onset of star formation activity in the association about 5 Myr ago, and
- a rather sudden termination of the star formation activity at most a few Myr later.

This scenario calls for some kind of external trigger that initiated the star burst in Upper Scorpius and some mechanism that terminated the star burst shortly thereafter. We believe that both effects were caused by massive stars.

4. The impact of massive stars on their environment

Massive stars, upwards of about ten solar masses, profoundly affect their environment in several ways (e.g. Garay & Lizano 1999). The most important factors are ionizing radiation, stellar winds, and supernova explosions.

O-type stars emit intense UV radiation that ionizes and heats the surrounding material. The strong ionizing radiation field next to massive stars can profoundly affect nearby cloud cores and the circumstellar material around young stellar objects by photoevaporation. This effect is nicely demonstrated by the proplyds in the Trapezium cluster (Bally et al. 1998; see also Richling & Yorke 1998; 2000).

Massive stars also have powerful winds that deposit considerable amounts of momentum and kinetic energy into their surrounding medium. Typical wind velocities of O-type stars often exceed 1000 km/sec, and typical values for the mechanical wind power are $\gtrsim 10^{36}$ erg/sec. A single O5 star can initiate the disruption of its parental cloud at a rate $\sim 10^{-2}\,M_\odot$/yr (cf. Yorke 1986), i.e. is perfectly capable of dispersing a $10^4\,M_\odot$ molecular cloud completely within only about 1 Myr.

Finally, after only $\sim 4 - 20$ Myr, the most massive ($\gtrsim 10\,M_\odot$) stars are expected to end their life with supernova explosions. Each supernova causes a strong shock wave that expands with initial velocities of $\gtrsim 10\,000$ km/sec and transfers typically some 10^{51} erg of kinetic energy in the ambient interstellar medium. The shock wave of the supernova will initially expand within the wind-blown bubble formed by the supernova progenitor. As soon as the supernova blast wave catches up with the bubble shock front, it will accelerate the expansion of the bubble (see e.g. Oey & Massey 1995 for numerical evolution models of wind- and supernova-blown bubbles) and further disrupt the parental molecular cloud (see e.g. Yorke et al. 1989).

5. Triggered star formation

Several recent numerical studies have dealt with the problem of a shock wave traveling through a molecular cloud and hitting cloud cores (e.g. Boss 1995; Foster & Boss 1996, 1997; Vanhala & Cameron 1998; Fukuda & Hanawa 2000). These studies found that the outcome of the impact of the shock wave on the cloud core mainly depends on the shock velocity: if the shock wave is faster than about 50 km/sec, the cloud core is shredded to pieces. If the shock wave is slower than about 10 km/sec, it causes only a slight temporary compression of the core. Shock waves with velocities in the range of $\sim 10-45$ km/sec, however, are able to induce collapse of molecular cloud cores.

A potential source of shock waves with velocities in that range are relatively distant supernova explosions. The supernova must neither be too close to the core (because then the shock wave will be too fast and destroy the core) nor too far away from the core (because then the shock wave will be too slow to trigger collapse). The appropriate range of velocities that are suitable to trigger molecular cloud core collapse roughly translates into a range of distances between 10 pc and 100 pc, the exact values obviously depending strongly on the details of the cloud structure and the evolutionary state of the pre-impact core. Other potential sources of shock waves with velocities in the desired range include wind-blown bubbles, expanding HII regions, and novae. Another interesting source of shock waves with typical velocities of a few tens of km/sec are protostellar outflows. Once a burst of star forming activity is started in a molecular cloud, e.g. triggered by a supernova shock wave, many of the forming stars will produce protostellar outflows and some of these outflows will hit other cloud cores and can be expected to drive them into collapse. This process might therefore well be able to provide a positive feedback to the star formation process and increase the star formation activity even further.

Several examples for triggered star formation have been discussed in the literature. For example, it has been suggested that star formation in the CMa R1 association (cf. Herbst & Assousa 1977) as well as the Cep OB3 association (cf. Assousa et al. 1977) has been triggered by expanding supernova shells. Oey & Massey (1995) discuss the dynamics of the superbubble H II region DEM 152 in the LMC and find evidence for triggered star formation. In the Cone nebula the formation of six young stellar objects is thought to be triggered by the wind from a B2 star at the center of the system (cf. Thompson et al. 1998). A good example of the positive feedback on the star forming activity provided by protostellar outflows might be the NGC 1333 star forming region: Knee & Sandell (2000) investigated the numerous molecular outflows in NGC 1333 and concluded that apparently secondary star formation has been and may continue to be triggered by the outflows of the protostars.

6. The triggered star burst in Upper Scorpius

In section 3 we concluded that the star burst in Upper Scorpius was probably triggered by some external effect. Interestingly, a suitable trigger is actually available and this allows us to draw a nice and consistent picture of the star formation history of Upper Scorpius (see also Fig. 4). As mentioned above, the Scorpius-Centaurus association is surrounded by several large H I loops, which were created by supernova explosions and stellar winds. The kinematic properties of the largest and thus oldest of these shells ($v \sim 10$ km/sec, radius ~ 110 pc) suggest that it was created by a supernova explosion in the Upper Centaurus-Lupus association about 12 Myr ago. The geometric and kinematic data suggest that this shock wave passed through the former Upper Scorpius

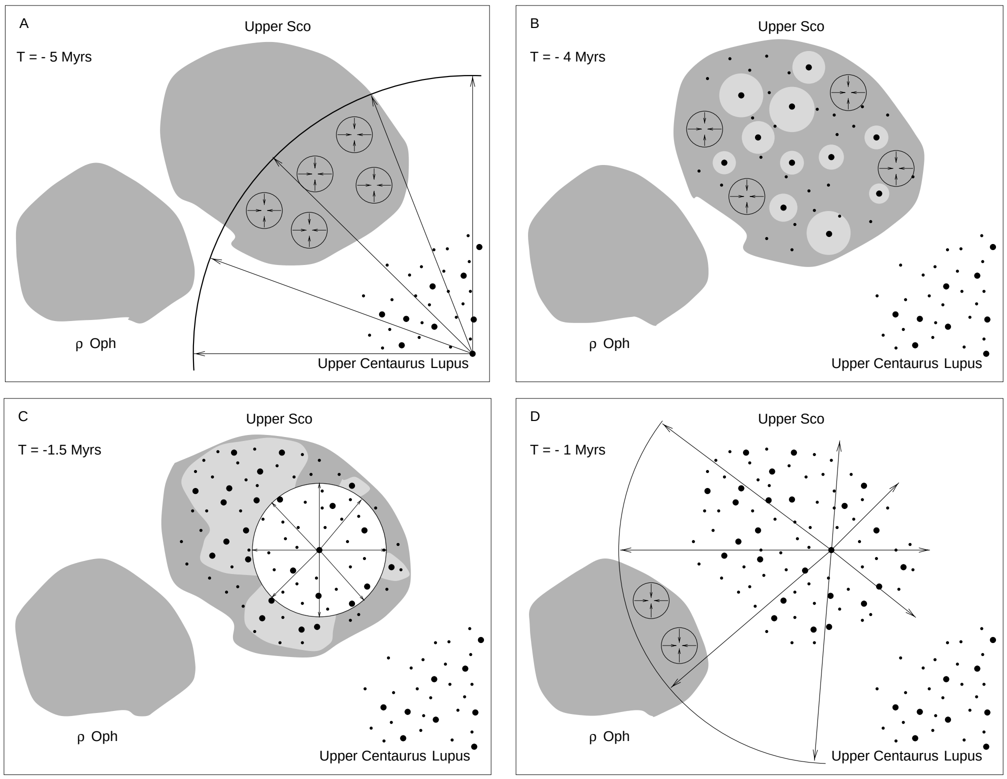

Figure 4. Schematic view of the star formation history in the Scorpius-Centaurus association. Molecular clouds are shown as dark regions, high-mass and low-mass stars as large resp. small dots. For further details see text.

molecular cloud just about 5 Myr ago (de Geus 1992). This point in time agrees very well with the stellar ages of the low-mass stars as well as the high-mass stars in Upper Scorpius, that have been determined in an absolutely independent way. Furthermore, since the distance from Upper Centaurus-Lupus to Upper Scorpius is about 75 pc, this shock wave probably had precisely the properties that are required to induce star formation according to the modeling results mentioned above. Thus, the assumption that this supernova shock wave triggered the star formation process in Upper Scorpius (cf. Fig 4a) provides a self-consistent explanation of all observational data.

During the star burst, probably more than 1000 stars formed within a period of at most 1–2 Myr. This suggests that there was a very large number (several hundreds) of protostellar outflows that might well have triggered further cloud collapse and accelerated the star formation rate. However, these outflows presumably also initiated the disruption of the molecular cloud. Cloud dispersion must have increased strongly after a few 10^5 years, when the new-born massive stars "turned on" and started to affect the cloud by their ionizing radiation and their strong stellar winds. The combined effect of numerous massive stars probably affected the cloud so strongly that after a period of $\lesssim 1$ Myr the star formation process was terminated, simply because all the remaining cloud material had been disrupted. This explains the narrow age distribution, i.e. the lack of stars that formed later than $\gtrsim 1$ Myr after the onset of the starburst.

Finally, we note that the most massive star in Upper Scorpius (presumably a $40\,M_\odot$ star, cf. de Geus 1992) exploded as a supernova about 1.5 Myr ago. The shock wave of this explosion fully dispersed the remnant cloud material in Upper Scorpius (cf. Fig. 4c), and must have reached the ρ Oph cloud within the last 1 Myr (cf. Fig. 4d). Interestingly, the ρ Oph cloud actually shows evidence for compression from the rear south-western side and for the presence of a slow shock (cf. Motte et al. 1998). It might well be that this shock wave now triggers the current burst of star formation in the ρ Oph cloud.

In summary, we conclude that the Scorpius-Centaurus OB association constitutes one of the best examples of triggered star formation.

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